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A toolpath-based layer construction method for designing & printing porous structure

Yicha Zhang (2)[a], Shujie Tan[b], Liping Ding[b], Alain Bernard (1)[c]

[a] UTBM – Université de Technologie Belfort-Montbéliard, ICB-COMM, CNRS UMR 6303, Sevenans, France
[b] College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, China
[c] Laboratory for Digital Sciences of Nantes (LS2N), Ecole Centrale de Nantes, France

Current porous structure design methods in additive manufacturing (AM) lose accuracy in data model transformations along the processing chain and are difficult to consider manufacturability and post-processing issues. In addition, the design and printing preparation is costly due to large number of fine features and their related operations. To solve these problems with an aim to save time in design and printing preparation but ensure manufacturability and easy post-processing, this paper proposes an implicit design method using printing toolpaths to construct printable parametric porous structures. Experimental case studies demonstrated the feasibility, efficiency and application potential of the proposed method.

Porous Structure, Tool Path, Additive Manufacturing

1. Introduction

The unique capability of dealing with complexity enables Additive manufacturing (AM) to play an important role in the fabrication of functional porous or lattice structures in wide application domains [1-3]. Some medical and industrial applications require designing and printing unit shapes with a size smaller than 200 microns [4]. However, as the decrease of feature size, the design (geometric modelling) and printing preparation become more and more difficult and costly since the number of cell units and resulted data file size increase dramatically [5]. In addition, the difference between 'as-designed' and 'as-printed' is always there, especially large for lattice or porous structures [6, 7]. To improve printing accuracy of porous structures, for a given CAD model, it is hard to balance the pre-processing time and the toolpaths' accuracy [8] since there are limitations in design data format and current build preparation methods. Furthermore, without the consideration of processing parameters or post-processing issues in design and build preparation, it is difficult to build the part 'first time right' [9], which brings more risks and cost. Hence, there is a need to investigate how to efficiently design and print porous structures with improved accuracy and ensured quality.

To meet this need, this paper introduces a new construction method using processing toolpaths to define printable porous structures within a given design space or boundaries via an implicit way. The proposed method can simplify the build preparation and decrease the loss of accuracy occurred in the model transformation stages, and at the same time consider manufacturability and post-processing issues. The left contents are organized as follows: the next section reviews the most related works and summarizes the existing problems; Section 3 introduces the proposed methods with details; Section 4 gives design and printing examples for method demonstration and Section 5 ends with a conclusion.

2. Related work

In AM processing chain, model design, STL file creation, and build preparation [10] are the main steps before printing. Therefore, the current methods to design and print lattice or porous structures follow these steps. In practice, designers need to design a quite complex CAD model with large number of unit shapes represented by boundary methods as used in conventional CAD tools. This usually causes large size of model file and difficulty for model manipulation and transformation, from original CAD model to STL model, from STL model to slicing model and from slicing model to toolpath model, in the printing preparation stage. The small change of the number and size of unit cells in a porous structure usually causes a large computation difference in the design and printing preparation. To avoid the loss of accuracy in slicing model transformation stage, some scholars had tried to overcome the inherent limitations of STL format by slicing an origin CAD model directly to obtain smooth slice boundaries [11-13]. However, the design of the explicit CAD model and the toolpath model generation are still costly. There is still accuracy loss and manufacturability issue in the toolpath model. To gain accuracy and efficiency for toolpath model generation, some researchers [14-16] worked on optimization algorithm for path planning. Nevertheless, they treat it as a pure geometric problem, rather than consider processing parameters and limitations as a whole. In addition, the number of contour islands of porous slices is huge, which costs much computation for path planning. More importantly, without processing compensation and adaptation for toolpaths, it cannot ensure manufacturability. To avoid the design complexity, some researchers adopted a random point seeds generation method to obtain porous structures [17]. This method can form porous structures with different pores in shapes and sizes, but it is hard to form regular controllable parametric periodic cellular porous structures for function control. Moreover, it neglected the problem of removing non-used raw powders locked by closed pores in the post-processing stage. In [18], authors present a toolpath filling method for printing triply periodic minimal surfaces (TPMS) in selective laser melting (SLM) process. However, similarly, they only focused on geometric compensation for wall thickness. It is not only still costly for the computation of large number of layer points, but also cannot ensure the validity and the manufacturability of toolpaths. When the unit structure becomes smaller, the infill area may decrease and cause severe re-melting problem in SLM process. Hence, omitting the manufacturability analysis in porous structure design may cause printing failure since processing parameters, e.g. laser power,

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scanning speed and laser beam, emission type, etc., directly define the physical toolpath's section profile and affect the final manufacturing accuracy [19, 20].

To sum up, current design and build preparation methods for porous structures have the following problems: **a**. accuracy loss exists in model transformation steps without suitable control, and **b**. there is no investigation on manufacturability since the processing parameters and post-processing are not considered. Hence, the method below is proposed to solve these problems.

3. Proposed method

3.1 Method overview

The proposed method directly starts from a hull model, which define the boundaries or design space of the porous structure. Then, characterized processing parameters and resulted melting path data sets are used to construct porous slice features inside the hull model layer by layer to form a 3D porous structure's toolpath data model. Fig. 1 describes the overview of the proposed method.

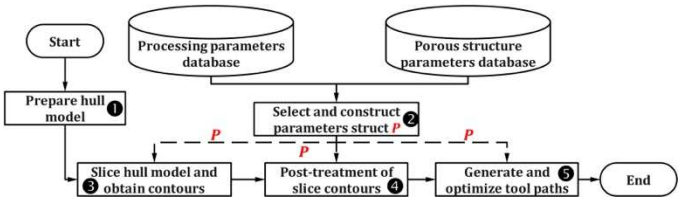

Figure 1. Workflow of the proposed toolpath-based construction method.

Step 1: *Prepare a hull model*

Opposite to the traditional design methods, this method here does not need to design a porous structure model with fine unit cell features represented in details, which extremely reduces computation time. In this step, a hull model, either an accurate boundary represented model or an STL approximation model, is prepared with consideration of porous structure patterns, general layouts and filling directions/angles. The role of the given hull is to provide geometric boundaries for filling toolpaths to construct the expected porous structure.

Step 2: *Set construction parameters*

To construct a toolpath data model to implicitly represent the expected porous structure model within a given hull, there is a need to choose two types of parameters, including processing parameter sets (benchmarked data sets) and porous structure patterns (symbolic or skeleton models). Processing parameters include laser power (**L_P**, W), scanning speed (**v**, mm/s), slicing thickness (**S_T**, mm) and spot compensation (**S_C**, mm), which have the same meaning as those used in commercial machines and software tools. Porous structure parameters include filling pattern, filling angle, unit size and some other specific parameters for different structures. A knowledge base stores these two types of data sets. According to a chosen unit cell size and shape for the desired porous structure, a suitable processing parameter set related to a benchmarked physical toolpath profile (e.g. melt bandwidth and profile in SLM) is selected for the later construction. The selection pair should ensure the manufacturability, e.g. available minimum feature size, necessary melting compensation, and construction accuracy.

Step 3: *prepare slice contour*

This step applies a set of parallel planes that are perpendicular to the printing direction to cut the hull model to obtain slice contours. Since uniformed layer thickness is widely used to enable multi-part printing scenario [21, 22], the parallel planes for cutting have a fixed layer thickness. It is similar to traditional slicing procedure. The objective is to find the intersection contours for each slice and these found contours are used as 2D boundaries of construction. The boundaries can be represented by spline curves or segment line-based polygons, which depends on the CAD model data format.

Step 4: post-treatment of slice contours

After slicing, each layer can obtain a slice contour or a set of coplanar contours. However, these contours cannot be directly used for path filling. The main reason is that the processing characteristics should be considered. There is a need of a special treatment. The post-treatment strategy depends on specific AM processes. Taking SLM process as an example, firstly, to overcome the loss of accuracy caused by the laser spot size during the melting process, contours need to be eroded at a distance (spot compensation). Then, if needed, contours can be decomposed into several different sub-contours for different filling patterns, such as denser regions and more porous regions (Fig. 2). At last, these regions should be attached to pre-selected processing parameter sets and porous structure patterns.

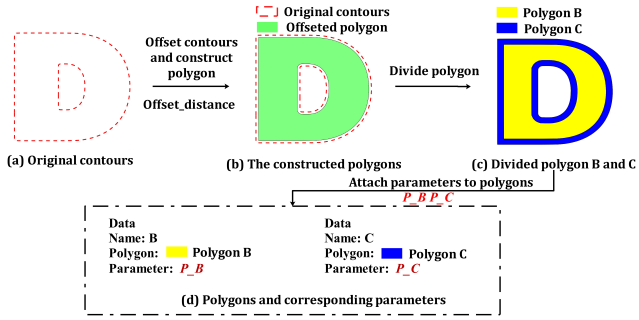

Figure 2. An example on post-treatment of slice contours.

Step 5: *toolpath generation & optimization for layer construction*

The last step is to generate and optimize toolpaths within each post-processed slice contours to construct grids or curved holes, which are used to approximate and represent the 2D slices obtained by slicing a porous structure CAD model. Different laser scanning patterns are used to construct different porous structures' 2D slices via specific designed combination scheme. By changing the scanning lengths, angles and directions within slice contours and offsetting & rotating slices in the printing direction, different porous structures can be obtained by assembling the constructed layers or slices in a construction way.

3.2 General construction procedure

In this paper, based on real application requirements, three main categories of porous structures are investigated. As shown in Fig. 3, they are 2D channel porous structures, 2.5D scaffold porous structures and 3D TPMS lattice as well as CAD models (in grey colour) designed by traditional CAD tools for visualization purpose.

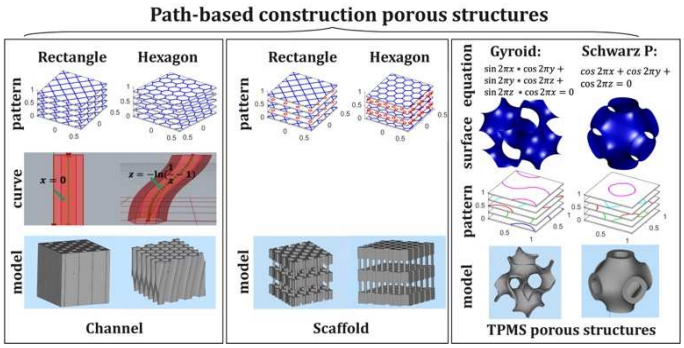

Figure 3. Three different categories of porous structures.

3.2.1 Layer construction of 2D channel porous structure

2D channel porous structure, such as honeycomb, is formed by repeating 2D polygon copies. For the straight channel, it has the same shape in every layer. While for the curved channel, it just

has an overall offset in different layer height to different in-plane directions. Fig. 4 shows the main steps of path-based layer construction for 2D channel porous structure: 1. Rotate a contour counter clockwise. The rotation angle is the filling angle, and the rotation centre is the origin of the coordinate system; 2. Calculate the offset distance based on curve equation of the channel's central axis; 3. Fill polygons with rectangle pattern or hexagon pattern (In fact, it is 'C' line. The polygon is assembled from two directions to form hexagons); 4. Rotate the filling lines clockwise; 5. Finally, optimize the sequence of filling lines for each layer to obtain the shortest scanning time.

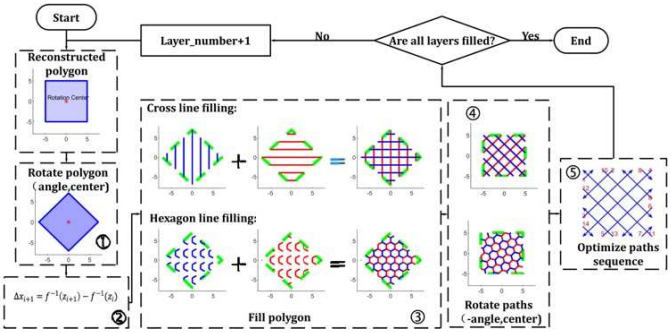

Figure 4. Layer construction for a 2D channel porous structure.

3.2.2 Layer construction of 2.5D scaffold porous structure

Unlike the 2D channel porous structure, there exist two different layers in 2.5D scaffold porous structure. One is the 2D polygon layer. The other is the pillar layer, which is composed of copies of 2D contours, such as circles, quadrilateral, hexagon, octagon and other polygons. Fig. 5 shows the workflow of layer construction for a pillar layer: 1. Seeds points in the slice contour. The distance between two points should respect the maximum bridge length criterion for AM process to avoid collapse of 2D polygon layer; 2. Rotate point grid and contour clockwise; 3. Create circles with points as arc centres and radius. Here lines' overlap in the circle are not considered since the radius used in this method is about 0.05 microns, which is smaller than the width of a melt track in AM; 4. Finally, optimize the jumping paths. The generation of jumping paths in different arc centres is treated as a travelling salesperson problem, and a genetic algorithm is used to solve it.

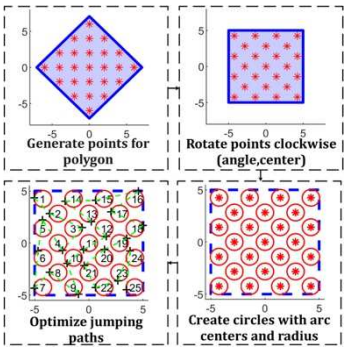

Figure 5. Layer construction (pillar) for a 2.5D scaffold structure.

3.2.3 Layer construction of 3D TPMS structure

TPMS lattice structure is determined by implicit mathematical functions. Hence, it is convenient to slice a single unit cell by using a set of parallel planes in the printing direction and obtain a set of corresponding accurate smooth 2D intersection curves. These 2D curves can be used to fill hull model's slice contours to construct TPMS structure's 2D slices. Fig. 6 describes the construction of a slice for a TPMS structure: 1. Generate gridline points for a slice contour; 2. Differentiate boundary points on the contour and the inner points within the contour; 3. Transform basic TPMS filling curves (obtained by slicing a unit cell at different printing heights) to the boundary points and inner points; 4. Intersect contour and boundary filling curves and clear the curves out of the slice contour; 5. Merge the inner curves in adjacent units to obtain a structure slice.

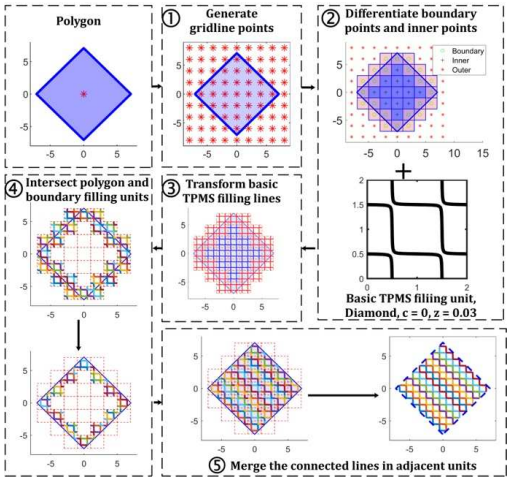

Figure 6. Layer construction for a diamond TPMS lattice structure.

Due to limited space, only three types of layer construction methods for three types of widely used uniformed porous structures are presented in this paper. Actually, with generative algorithms and suitable layer transformation schemes, a large number of layer construction methods can be developed in a combinatorial way for different porous structures. Hence, specific databases can be built for specific AM processes according to application requirements. Globally, the proposed method enables parametric control of fine porous features in an implicit way, which is very important for manufacturability checking, e.g. minimum printable feature of AM processes, and post-processing issues, such as the control of the size and interconnection of pores to facilitate the removing of non-used raw materials, e.g. powders in SLM, after printing.

4. Case study

In this section, a comparison case study is presented for demonstration. Three cubic porous structure samples, 2D channel, 2.5D scaffold and TPMS, with a 10x10x10 mm^3 size are designed by the proposed method and an efficient traditional method (Rhino CAD tool) respectively and printed in SLM process. Table 1 shows the processing parameters for the two groups of parts (***p***-group for this method and ***r***-group for traditional method). Toolpath-based method has parameter optimization and simplification, while the traditional method applies standard similar processing parameter setting since commercial preparation tools define this. Two key indicators, total design & printing preparation time (in quantitative) and visible printing quality & post-processing convenience (in qualitative), are used in the comparison. In the design stage, the parametric model building time is not considered for comparison since it depends on designer's skill, while the parametric model updating time (change design parameter for model updating) is measured because it is a pure computation time. Figure 7 shows the workflows of the two methods. All the steps of the proposed methods were implemented in MATLAB environment without code optimization, while those of the traditional method were implemented by a set of commercial tools that should be the most suitable and efficient for the related operations to the authors' knowledge. It should be noted that the example samples are quite simple to enable the comparison since more complex porous

structure models cannot be realized by using commercial tools. Table 2 and Figure 8 present the results.

Table 1. Processing parameters for the two groups in comparison

	No.	*S_T (mm)*	*V (mm/s)*	*L_P (W)*
p-group	1-p	0.03	1200	90
	2-p	0.03	1200	90
	3-p	0.03	1800	90

		S_T (mm)	*C_v (mm/s)*	*C_L_P (W)*	*F_v (mm/s)*	*F_L_P (W)*	*H (mm)*
r-group	1-r 2-r 3-r	0.03	1200	90	850	90	0.08

Note: ***S_T***-slicing thickness, v-scanning speed, ***L_P***-Laser power, ***C_v***-contour's scanning speed, ***C_L_P***-contour's laser power, ***F_v***-filling segments' scanning speed, ***F_L_P***-filling segments' laser power, ***H***-hatch space (only some of the important parameters in SLM are presented here).

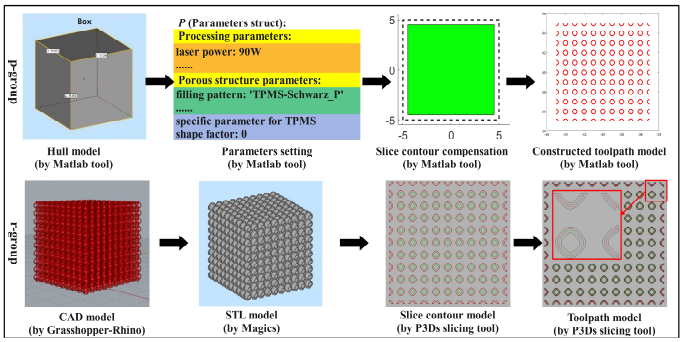

Figure 7. Design & printing preparation workflows of the two groups.

Table 2. Comparison results between path-defined and rhino-designed porous structures.

No.	1-p	1-r	2-p	2-r	3-p	3-r
Model updating time (s)	***null***	592	***null***	547	***null***	305
STL Conversion time (s)	***null***	166	***null***	437	***null***	243
Path generation time (s)	385	154	302	184	101	530
Total (s)	**385**	912	**302**	1168	**101**	1078

Note: 1. no design, STL conversion and repairing time for ***p***-group; 2. STL repairing time is neglected for ***r***-group.

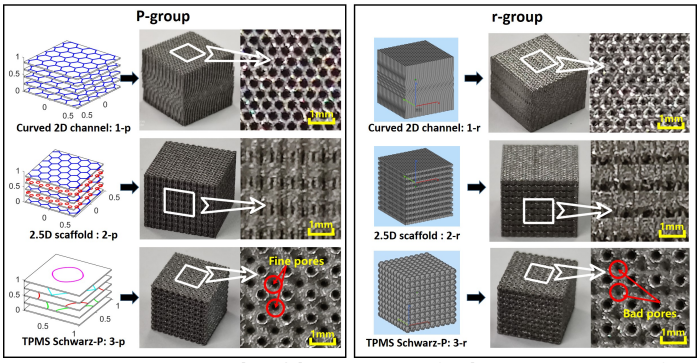

Figure 8. Printing results of the two groups (without post-processing)

According to the experiment results, observations are found as: **a.** the total pre-processing time has been greatly reduced for the ***p***-group. **b.** ***p***-group has better printing result without crack and collapse and can achieve a higher shape accuracy; **c.** the minutiae of the ***p***-group is very good while the ***r***-group is blurred; **d.** the removing of the non-used powder for the ***p***-group is quite easy while there a lot of powders are blocked in the ***r***-group. These differences are consistent as expected since the proposed method uses processing toolpaths to design structures in an implicit way with consideration of pore size control and pore interconnection for shape accuracy control and powder removing, but the traditional method only relies on explicit geometric operations, which causes severe accuracy loss and neglect toolpath compensation for manufacturability checking and post-processing. Hence, printing defects and locked powders exist. The only inconvenience of the proposed method is the difficulty to view the full CAD model since toolpath model is used to implicitly represent the expected CAD model. But, theoretically, with toolpaths and the deposition section profiles, a CAD model can be generated by a set of costly Boolean operations.

5. Conclusion

Toolpath-based construction method can efficiently design and printing porous structures with ensured manufacturability. It has much potential to replace the current porous structure design and printing preparation methods in industry. Processing knowledge and the design of construction algorithm are the key factors for the proposed methods. In the future work, the authors will investigate how to integrate printing numerical simulation with the proposed method to gain more accuracy and efficiency.

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